3-Phase Converter Modeling for Unbalanced Radial Systems [1]

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Outline

- Overview
- Modeling Approach
- Application to Power Flow
- Simulation Results
- Summary
- Current & Future Work

Overview

US Navy and Shipboard Systems:

- Moving towards all-electric ships and prolific use of new converter technologies
- Reduced manning efforts require automation

Power Distribution Systems:

- Upgrading equipment
  - power electronic switching
- Many single and two-phase sections

End Goal:

- Performance Indices for Systems with Multiple Converters

Overview

Previous models:

- initially, designed for transmission systems - HVDC
- single-phase models
- three-phase models with balanced operating conditions

Modeling Efforts:

- unbalanced converter models for steady-state analysis

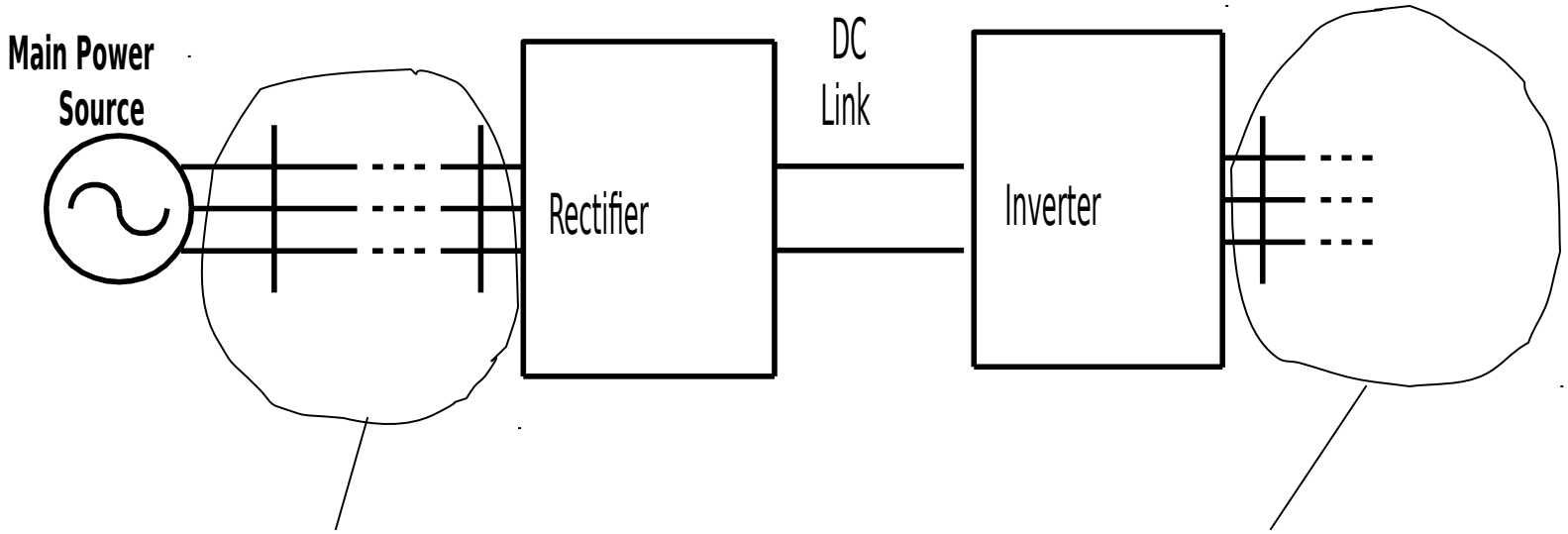
Converter Models (1/7)

New models:

- able to capture operation in unbalanced networks
- easily incorporated into existing power flow solvers
- two models to handle different rectifier control schemes:
  - *uncontrolled rectifiers (equivalent 3-phase converter model)*
  - phase-controlled rectifiers with equi-distant firing angle (P|I| bus model)

- two models to handle different converter control schemes:
  - *PWM inverter switching (voltage source inverter)*
  - 6-pulse phase controlled with individual extinction angle control (additional commutation time equation)

Converter Models (2/7)

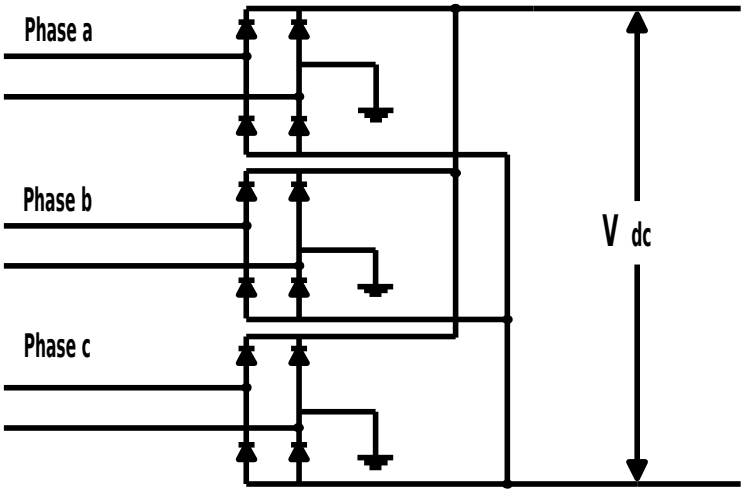


(A) rectifer model

(B) dc – link

(C) inverter model

Converter Models (3/7)



Equivalent Rectifier Model

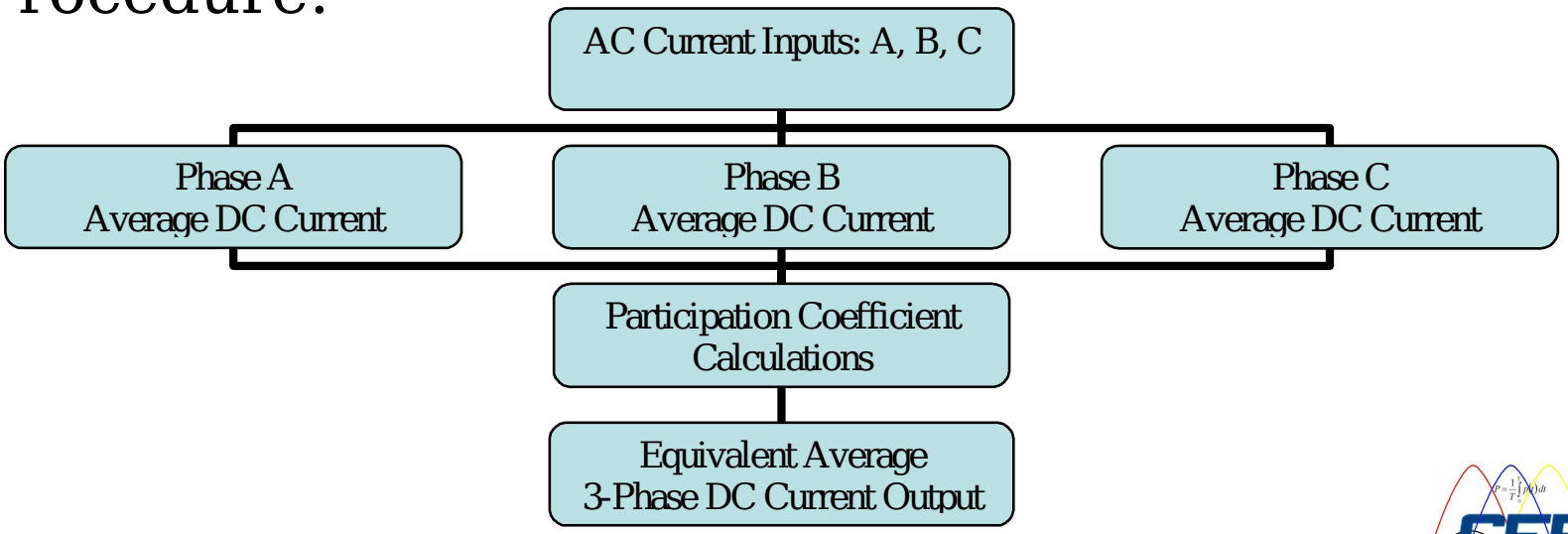
- Built using 3 grounded Y-connected 1-phase rectifiers
- Each 1-phase rectifier is a diode bridge rectifier
- Input: unbalanced 3-phase ac
- Output: dc link

Converter Models (4/7)

Equivalent Rectifier Model Features:

- *equivalent* with respect to the average output current with a 3-phase rectifier
- employs participation coefficients which describe the contribution of each phase to the dc current

Procedure:



Converter Models (5/7)

DC Link:

- Modeled as a pure dc circuit
- Considers real power loss

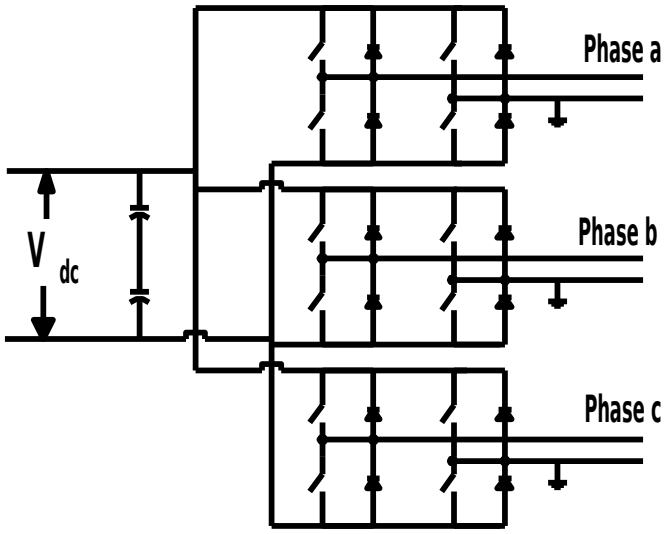
Inverter:

- 3 Y-connected single-phase voltage source inverters
- Negligible ripple
- Uses the fundamental component of the output signal

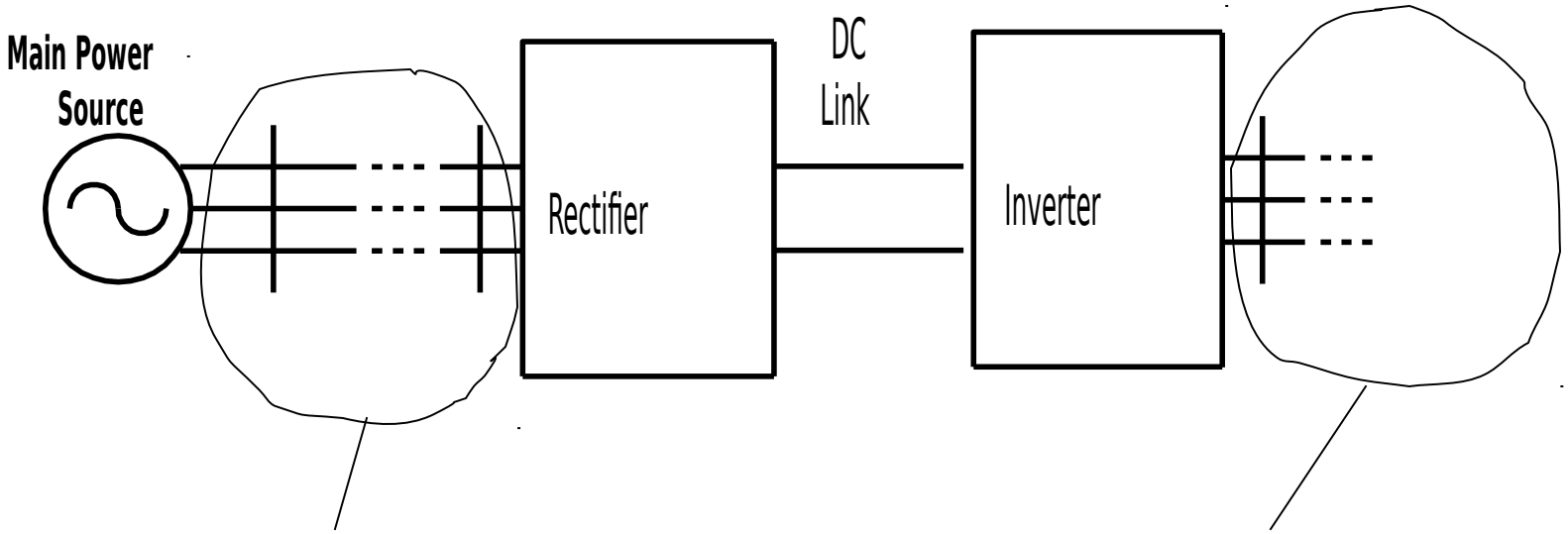
Converter Models (6/7)

Equivalent Inverter Model

- Built using 3 grounded Y-connected 1-phase inverters
- 1-phase inverters are pwm inverters
- Input: dc link
- Output: 3-phase ac system



Converter Models (7/7)



ac side of the rectifier **ac side of the inverter**

$$\begin{bmatrix} f_{ac}(x_{ac}, x_{dc}) \\ f_{dc}(x_{ac}, x_{dc}) \\ f_{converter}(x_{ac}, x_{dc}) \end{bmatrix} = 0$$

Radial Distribution Power Flow (1/2)

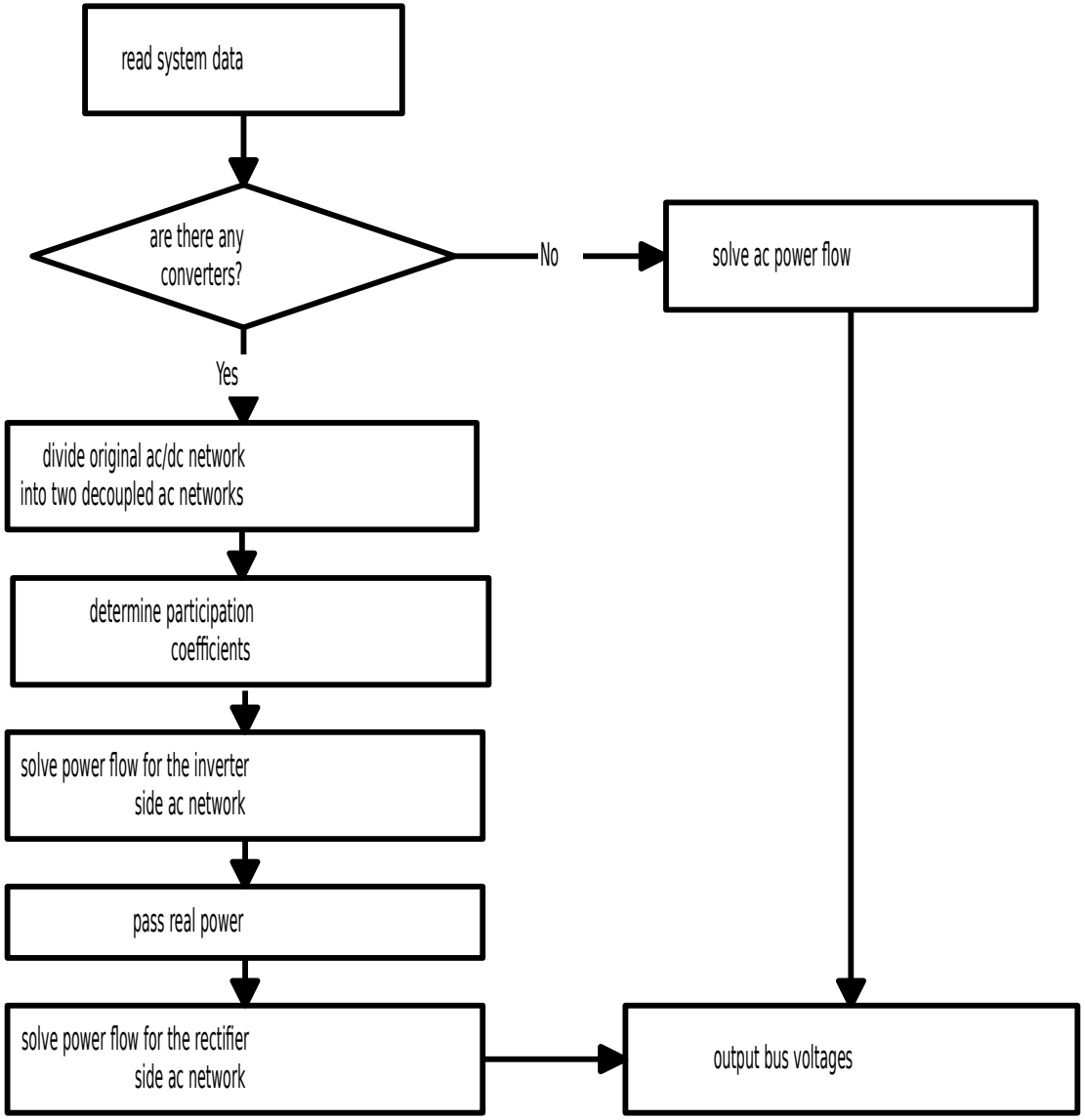
Assumptions:

- direction of the *average* power flow: from the rectifier to the inverter
- PWM inverter acts as a voltage source

Features:

- sequential power flow (ac portion, then dc portion)
  - ac inverter side
  - dc link
  - ac rectifier side
- avoids convergence problems because of
  - the assumed single direction of average
  - existence and uniqueness results for unbalanced radial systems [2000 – Miu & Chiang]

Radial Distribution Power Flow (2/2)


read system data
are there any converters?
No
solve ac power flow
Yes
divide original ac/dc network into two decoupled ac networks
determine participation coefficients
solve power flow for the inverter side ac network
pass real power
solve power flow for the rectifier side ac network
output bus voltages

Simulation Results (1/3)

A 15-bus, 12.47kv, unbalanced radial network:

- Converter between bus 4 & 5 (practical installation inc. filtering/nec. xfmrs)
- 4 loads
  - two unbalanced: bus 3 & 16
  - Two balanced: bus 10 & 15
  - a grounded-Y to grounded-Y transformer connected between buses 12 and 13 (XFMR)

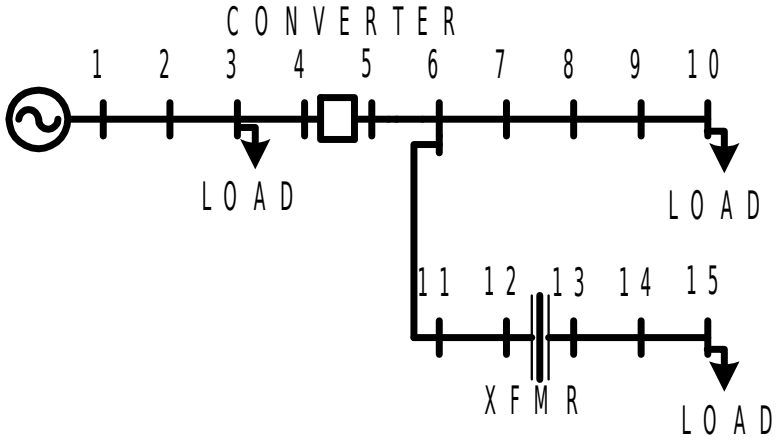


Figure. A one-line diagram of the 15-bus network system
NOTE: bus 16 is connected by a 1-phase line after bus 15.

Simulation Results (2/3)

Table I. Power Delivered to the Loads in [MW,MVAR]

Bus	*P+jQ; Phase a*	*P+jQ; Phase b*	*P+jQ; Phase c*
3	0.1993	0.3981	0.7959
10	0.5312+j0.2656	0.5314+j0.2657	0.5313+j0.2657
15	0.5219+j0.2609	0.5253+j0.2627	0.5250+j0.2625
16	0.1956+j0.0978		

Table I. Participation Coefficients for Phases *a*, *b* and *c*

λ_a	λ_b	λ_c
0.333184	0.333385	0.333431

Simulation Results (3/3)

Table XI. Power Entering (4) and Leaving (5) the converter in [MW,MVAR]

Bus	*Phase a* *P+jQ*	*Phase b* *P+jQ*	*Phase c* *P+jQ*
4	1.1234+j1.3560	1.1234+j1.3561	1.1234+j1.3562
5	1.2524+j0.6391	1.0587+j0.5364	1.0588+j0.5361

Summary

- Models for unbalanced converter operation can be derived that are suitable for large-scale systems studies
- Three-phase components can be equivalenced to three, single-phase Y-connected components
- The models can be easily incorporated into sequential power flow algorithms
- If average power flow is uni-directional, convergence is expected.

Current and Future Work

- 6-pulse phase controlled rectifier models with equi-distant firing angles are being rigorously tested
- 6-pulse phase controlled inverter with individual extinction angle control models are being rigorously tested
- Hardware laboratories are under development to verify derived models